Neutrino Oscillations, Solar Antineutrinos and the Solar Magnetic Fields

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Abstract

Even after the confirmation of the large mixing angle (LMA) solution of the solar neutrino problem, the scope for resonant spin- flavor precession (RSFP) transitions as a subdominant effect still exists. In this work,we have considered suitably suppressed RSFP transitions in addition to the dominant LMA flavor transitions and translated the bounds on the antineutrino flux into the bounds on the product of neutrino magnetic moment and solar magnetic field. The low and intermediate energy neutrinos have been included in the analysis by obtaining indirect bounds on the corresponding antineutrino fluxes for these components. It is assumed that the missing beryllium neutrinos are being converted into muon antineutrinos via RSFP transitions in the Sun.

1 Introduction

The neutral current measurements at SNO [1] have confirmed the oscillations of solar neutrinos. After the first evidence of antineutrino disappearance in a beam of electron antineutrinos reported by KamLAND experiment [2], all other explanations of the solar neutrino problem are either completely discarded or may just be subdominant effects. After these pioneering experiments, there is hardly any scope for doubt about the physical reality of neutrino mass and their, consequent, oscillations. Once neutrino mass is observed, neutrino magnetic moments are an inevitable consequence in the Standard model and beyond.

KamLAND is the first experiment to explore the neutrino parameter space relevant to solar neutrinos with a beam of terrestrial neutrinos. KamLAND has, convincingly, demonstrated the existence of neutrino oscillations with parameters confined to the LMA region. Apart from the measurement of reactor antineutrino flux, KamLAND is sesitive to any boron antineutrinos produced from solar boron neutrinos as a result of spin flavor oscillations. The flux of solar antineutrinos is expected to be considerable, in case, the neutrinos possess Majorana character and, in addition, the neutrino magnetic moment is high enough. Thus, the observation of a small solar antineutrino flux is likely to establish the Majorana character of the neutrino and the existence of physics beyond the Standard Model. An important signature of RSFP is an observable flux of electron antineutrinos from the Sun if neutrinos, in addition to transition magnetic moments, have a sizable flavor mixing. The flux of solar electronic antineutrinos can, in principle, be detected at BOREXINO and SNO. If both transition magnetic moments and flavor mixing of massive neutrinos are present, the combined action of RSFP and the flavor oscillations may lead to an observable flux of electron neutrinos. The existing bounds on the solar antineutrino flux from KamLAND are fairly stringent [3].

It may be worthwhile to emphasize again that the observation of solar electronic antineutrino flux will be a unique signature for a Majorana neutrino transition magnetic moment and the resonant spin-flavor precession inside the Sun. Therefore,the results of the electronic antineutrino flux measurements by BOREXINO will be eagerly awaited since the sensitivity of BOREXINO to the electronic antineutrinos is expected to be about 37 times larger than that to the electronic neutrinos. The detection of solar antineutrinos is one of the major goals of several existing and forthcoming solar neutrino experiments.

The KamLAND bounds on the boron antineutrino flux are available now [3] and the beryllium antineutrinos will be observable in BOREXINO. SNO has already indicated that the solar electron neutrinos are being converted into active neutrinos by observing the neutral current processes [2]. Therefore, only a small fraction of electron neutrinos is allowed to be converted into the muon antineutrinos via the RSFP mechanism within the solar interior. These muon neutrinos can, then, oscillate into the electron antineutrinos while

travelling from the solar surface to the earth via vacuum transitions with a probability of about half. The bounds on the antineutrino flux have been used to obtain the bounds on μB for the case of high energy boron neutrinos [3]. After KamLAND results and earlier SNO neutral current measurements, there is hardly any doubt about the fact that the neutrino oscillations with LMA parameters explain the solar neutrino deficit and that the electron neutrinos are being, dominantly, converted into muon neutrinos. Only a small fraction is allowed to be converted into antineutrinos via RSFP mechanism.

In this work, we consider the solar antineutrino production in the RSFP scenario[4] in coexistence with the LMA MSW scenario and reexamine the earlier results for boron neutrinos. We also extend our analysis to include the low and intermediate energy neutrinos which have not been considered in the earlier analyses [3]. In order to obtain bounds on low and intermediate energy antineutrino fluxes, we compare the model independent values of the survival probabilities with their values in the pure LMA case assuming that the difference between the two is due to the RSFP driven $v_e \rightarrow \overline{v_\mu}$ transitions. It is noted that beryllium neutrino flux is smaller than the LMA expectations. This could explain the low Ar-production rate in the Homestake experiment sought to be explained by Smirnov [5] by invoking the existence of a light sterile neutrino. In this work, we surmise that the missing beryllium neutrinos are being converted into muon antineutrinos via RSFP transitions within the Sun. The muon antineutrinos, thus produced, undergo vacuum oscillations into the electron antineutrinos in their flight to the earth. This antineutrino flux can be detected by BOREXINO. Thus, the hypothesis advanced in the present work can be directly confirmed or discarded by BOREXINO in contrast to the hypothesis put forth by Smirnov [5] where the missing beryllium neutrinos are assumed to be oscillating into sterile neutrinos. In this scenario, the neutrino transition magnetic moments and solar magnetic fields required to account for the $v_e \rightarrow \overline{v_\mu}$ conversion of missing beryllium neutrino flux are well within their known limits . In order to avoid an anomalously large RSFP conversion of boron neutrinos, the magnetic field has to undergo a decrease towards the edge of the core. A suitably decreasing magnetic field profile also explains the absence of the rise up of neutrino energy spectrum at SuperKamiokande. This rise up can be as large as 10 percent in the pure LMA scenario [5].

2 Solar Magnetic Fields and Antineutrino Production

In our model of antineutrino production, the $\nu_e \rightarrow \nu_\mu$ flavor transitions are described by the LMA scenario while the $\nu_e \rightarrow \overline{v}_\mu$ transitions are described by the RSFP scenario where both types of transitions are assumed to be occurring independently of each other. This approximation is well justified for the LMA oscillation parameters for which the RSFP

resonance width is too small to interfere with the LMA flavor transitions [6].

The RSFP resonance condition [6]

$$\frac{5G_F N_e}{3\sqrt{2}} = \frac{\Delta m^2 \cos 2\theta}{2E} \tag{1}$$

implies that for the neutrinos of energy E , the resonance will occur at the point

$$x = 0.09 \ln\left(\frac{E}{0.45}\right) \tag{2}$$

where $\Delta m^2 = 7.1 \times 10^{-5} eV^2, \sin^2 2\theta = 0.9$, and we have considered the standard model density profile [7]. Here $x = \frac{r}{R_S}$ and the energy E is in the units of MeV. Boron neutrinos have average energy 6.7 MeV. The production region of the boron neutrinos extends up to x=0.15 [7] . Thus, in the course of their propagation, the boron neutrinos will get the resonance density at x=0.24. The resonance point for the beryllium neutrinos ($E = 0.861 MeV$) will be at x=0.06 which is near the point of maximal production [7]. Thus, the production and the resonance regions may coincide for the ^{7}Be (0.861 MeV) neutrinos for certain values of LMA parameters . This makes the LMA transition probability for beryllium neutrinos about half. However, the adiabatic RSFP transition probability for beryllium neutrinos is very small for values of μB within the range constrained by various laboratory and astrophysical bounds. Therefore, the non-adiabatic effects in the resonance region will be important. As the energies of the low energy pp neutrinos are below 0.45 MeV, they will not get the resonance densities anywhere.

The production region for the neutrinos is an extended one. For the pp neutrinos the maximal production occurs at the point x=0.1 whereas for the boron and beryllium neutrinos, the maximal production occurs at about x=0.05 [6]The mixing angle in matter in the presence of a magnetic field is given by [5]

$$\tan 2\widetilde{\theta}_m = -\frac{s_R}{s_\Delta} \tag{3}$$

where

$$s_R = 2\mu B, s_\Delta = \frac{5G_F N_e}{3\sqrt{2}} - \frac{\Delta m^2 \cos 2\theta}{2E} \tag{4}$$

The RSFP transition probability is given by

$$P(\nu_e \to \overline{\nu}_\mu) = \frac{1}{2} - \left(\frac{1}{2} - P_c\right) \cos 2\widetilde{\theta} \cos 2\widetilde{\theta}_{edge} \tag{5}$$

where $\cos 2\widetilde{\theta}$ is to be evaluated at the production point whereas $\cos 2\widetilde{\theta}_{edge}$ is to be evaluated at the edge and is approximately one. The crossing probability given by

$$P_c = \exp\left(-\frac{2s_R^2 E}{\Delta m^2 \cos 2\theta} 0.09 R_s\right) \tag{6}$$

is to be evaluated at the respective resonances [5]. For LMA parameters, it simplifies to $P_c = \exp\left(-4440.7 s_R^2 E\right)$ where s_R is in the units of $10^{-11}eV$ and E is in the units of MeV. For beryllium neutrinos, we have $s_\Delta = 0.12 \times 10^{-11}eV$ .For the boron and pp neutrinos, we have $s_\Delta = 1.28 \times 10^{-11}eV, -3.42 \times 10^{-11}eV$ at the respective production points for their respective average energies.

The bounds on μ are available from the various sources [8]. The reactor bounds on the neutrino magnetic moment are $\mu \leq 10^{-10}\mu_B$. The bounds on B [9] are less certain and little is known about its magnitude and spatial variation, especially in the deep solar interior. We can safely assume that $B \leq 1000T$ in the solar core. For $B = 10000T$, the SFP adiabatic transition probability is 0.64 for pp neutrinos. A considerable transformation into antineutrinos is,thus, allowed, even in the adiabatic approximation. Hence, such a large field is directly ruled out by virtue of the reactor bounds on the neutrino transition moments. This lowers considerably the Chandershekhar bound on B [10].

We, therefore, take $\mu = 10^{-10}\mu_B, B = 1000T$ as an upper bound, which implies $s_R = 1.16 \times 10^{-11}eV$. There will be considerably large adiabatic transitions for this value of s_R. The values of cos2θ for pp , beryllium and boron neutrinos are 0.96, -0.12 and -0.78 respectively. Thus, the transition probability is 0.02 for pp neutrinos in the adiabatic approximation which is justified for pp neutrinos because they do not undergo resonance. For Be and B neutrinos,the crossing probability is not zero and will be the only effect for smaller values of μB. For pp neutrinos, the transition probability (adiabatic) will approach zero as μB decreases. If $2\mu B$ is one order of magnitude below the above upper bound, *i.e.* $2\mu B \leq 10^{-12}eV$(e.g.$\mu \leq 10^{-12}\mu_B, B \leq 1000T$), the transition probability is $\leq 2.2 \times 10^{-6}$ for the pp neutrinos. For the beryllium and boron neutrinos, $\cos 2\theta \sim -1$ so that the adiabatic transition probability will be zero for them. Therefore, the transition of pp neutrinos into antineutrinos is not expected at all and the transformation of beryllium and boron neutrinos is highly non-adiabatic (adiabatic transition probability being zero). Hence, for the intermediate and high energy neutrinos, we have

$$P(\nu_e \to \overline{\nu}_\mu) = 1 - P_c \tag{7}$$

for $\mu \leq 10^{-12}\mu_B, B \leq 1000T$.

The bounds on antineutrino flux produced from the ^{7}Be neutrinos will be provided by BOREXINO. From these bounds, one can constrain μB within the core. Conversely, assuming suitable values for μB, one can predict the beryllium electron antineutrino probability and, hence, the beryllium electron antineutrino flux.

The probability for the electron antineutrinos to appear at the earth is given by

$$P(\nu_e \to \overline{\nu}_e) = P_{RSFP}(\nu_e \to \overline{\nu}_\mu) P_{VAC}(\overline{\nu}_\mu \to \overline{\nu}_e) \tag{8}$$

where, $P_{VAC}(\overline{\nu}_\mu \to \overline{\nu}_e) = \frac{1}{2}\sin^2 2\theta$.

Alternative models of antineutrino production studied in the literature [3] either consider a highly chaotic magnetic field in the radiation zone of the Sun or use perturbation calculations [valid only for small μB] to obtain the RSFP transition probability. In perturbative calculations, the transition probability depends only on the magnetic field in the production region. In both categories of models, the transition probabilities for beryllium and boron neutrinos can not be much different. Thus, these models can not explain a large transition probability for beryllium neutrinos into antineutrinos while still keeping the boron antineutrino production at a phenomenologically acceptable level, in contrast to the model considered in the present work.

The model independent survival probabilities for the low, intermediate and high energy neutrinos have been calculated from the solar neutrino data by Barger *et al* [11]. The survival probability for high energy neutrinos can be obtained from SNO NC and CC measurements alone the value for which in the pure LMA scenario is $\sin^2\theta = 0.34$. The agreement between the two values is the first step towards the solution of the solar neutrino problem. The experimental values, however, do not agree with the survival probabilities in the pure LMA scenario for low and intermediate energy neutrinos. The survival probability for the beryllium neutrinos is expected to be nearly half in the pure LMA scenario compared to the value of 0.3 obtained from the model independent analysis of the solar neutrino data [11] poinitng towards a significant portion of this component to be missing [12]. The two values do not agree even if the uncertainties in the experiments and the SSM fluxes are taken into consideration. Similarly, the LMA survival probability for pp neutrinos is the same as the vacuum survival probability $\left(1 - \frac{1}{2}\sin^2 2\theta\right) = 0.55$ whereas the experimental value is about 0.8 [11]. Thus, the observed pp neutrino flux is larger than the LMA expectation. Therefore, there is no scope for antineutrino production in the low energy range.

The missing beryllium neutrino flux can account for the low Ar-production rate at Homestake sought to be explained by Smirnov [5] by invoking mixing with a sterile component. It is clear that a portion of the beryllium neutrinos is undergoing other subdominant transitions in addition to the dominant LMA flavor oscillations. These transitions have to be effective only at the intermediate energies. An attractive candidate for these are the RSFP transitions, though, the transitions into a light sterile neutrino can also explain this anomaly [5]. The attractiveness of the RSFP transitions of missing beryllium neutrinos into antineutrinos lies in the possibility of their direct detection at BOREXINO. If the event rate at BOREXINO is found to be smaller than $R_{BOREXINO} \simeq 0.5$ (pure LMA value), it would confirm that a portion of the beryllium neutrinos are missing. In addition, if BOREXINO,also, observes an antineutrino flux of about 0.1 of the SSM beryllium neutrino flux, it would be confirmed that the missing beryllium neutrinos are undergoing RSFP transitions. Otherwise, the possiblity of oscillation into the sterile neutrinos has to be taken seriously.

Similarly, the RSFP transitions of boron neutrinos will result in values of the fluxes

smaller than the LMA expectations. In the pure LMA scenario, the flux of boron neutrinos is expected to increase slightly as the energy decreases. This rise up in the neutrino energy spectrum can be as large as 10 percent [5]. The possibility of RSFP transitions can result in a decrease in the neutrino flux which can explain the lack of the rise up of the boron neutrino spectrum at low energies.

From equations (5), (6), and (7), it follows that to account for the missing beryllium neutrinos via RSFP tarnsitions, we require $2\mu B \sim 7.6\times10^{-14}eV, (e.g. \mu \sim 10^{-12}\mu_B, B \sim 328T)$ deep inside the core ($x \sim 0.05$). To explain the upper limit on the boron antineutrino appearance probability (about 0.0034) obtained at KamLAND [3], we must have $2\mu B \sim 3.18\times10^{-15}eV, (e.g. \mu \sim 10^{-12}\mu_B, B \sim 13.7T)$ towards the edge of the core ($x \sim 0.25$). The recent direct bounds on the solar magnetic field at the bottom of radiation zone are: $B = 300-700T$ [13] which are independent of the values of the neutrino magnetic moment. If these bounds are to be taken seriously, we must take $\mu \sim (3.9-9.2)\times10^{-14}\mu_B$ to have the required value of $2\mu B$ at $x \sim 0.25$. Thus, a magnetic field of the order of about 10000T is required deep within the core.

From the equations (5),(6) and (7), and the rise up in the pure LMA survival probability, one can calculate the solar magnetic field profile. If $P_{LMA}(E)$ is the energy dependent survival probability in the LMA scenario, we must have

$$P_{LMA} = 1 - P_c + \sin^2\theta \tag{9}$$

in order to have no rise up in the boron neutrino spectrum at SuperKamiokande where the effects of flux-averaging over the production region have been neglected. The pure LMA survival probability [14] as a function of energy is given by

$$P_{LMA}(E) = \frac{1}{2} + \frac{1}{2}\cos 2\theta \cos 2\theta_m \tag{10}$$

where

$$\tan 2\theta_m = \frac{\sin 2\theta}{\cos 2\theta - 2\sqrt{2}G_F N_e E/\Delta m^2}$$

The LMA survival probability $P_{LMA}(E)$ has been ploted in Fig.1.as a function of energy E (in the units of MeV). The rise up in the survival probability for boron neutrinos at low energies is about 4 percent. Also, for the average value of energy (6.7 MeV), $P_{LMA} = 0.3480$ while $\sin^2\theta = 0.3418$. This implies an electron antineutrino appearance probability of 0.0031 in fairly close agreement with the KamLAND bound [3].

The magnetic field profile in the resonance region of boron neutrinos extending from 0.2 to 0.3 can be obtained, directly, from equation (9). In Fig.2., the magnetic field B(in the units of Tesla) has been plotted against the distance from the center of the Sun in the units of the solar radius, assuming $\mu \sim 10^{-13}\mu_B$.

3 Conclusions

To conclude, we considered the solar antineutrino production via RSFP transitions in coexistence with the dominant LMA MSW transitions to explain the KamLAND bounds on solar antineutrinos. The bounds on the antineutrino flux have been translated into the bounds on solar magnetic fields. Recent studies [3] on solar antineutrinos are limited to boron antineutrinos for which direct bounds are available from KamLAND. However, we have incuded low and intermediate energy neutrinos in this analysis. Indirect bounds on low and intermediate energy antineutrino fluxes have been obtained by comparing the model independent values of the survival probabilities obtained from the solar neutrino data with their values in the pure LMA case. It is noted that beryllium neutrino flux is smaller than the LMA expectations implying that the beryllium neutrinos are also undergoing transitions other than the flavor oscillations at a subdominant level. A natural candidate for these transitions are the spin-flavor transitions which can result in lower event rate at BOREXINO as compared to the pure LMA expectations. Whether this is actually happening can,directly, be verified by BOREXINO. The neutrino transition moments and solar magnetic fields required to account for the missing beryllium neutrino flux are well within the known limits on these quantities. Moreover, to avoid an anomalously large RSFP conversion of boron neutrinos, the magnetic field has to undergo a decrease towards the edge of the core. In addition, a suitably decreasing magnetic field profile can also explain the absence of the rise up of neutrino energy spectrum at SuperKamiokande.

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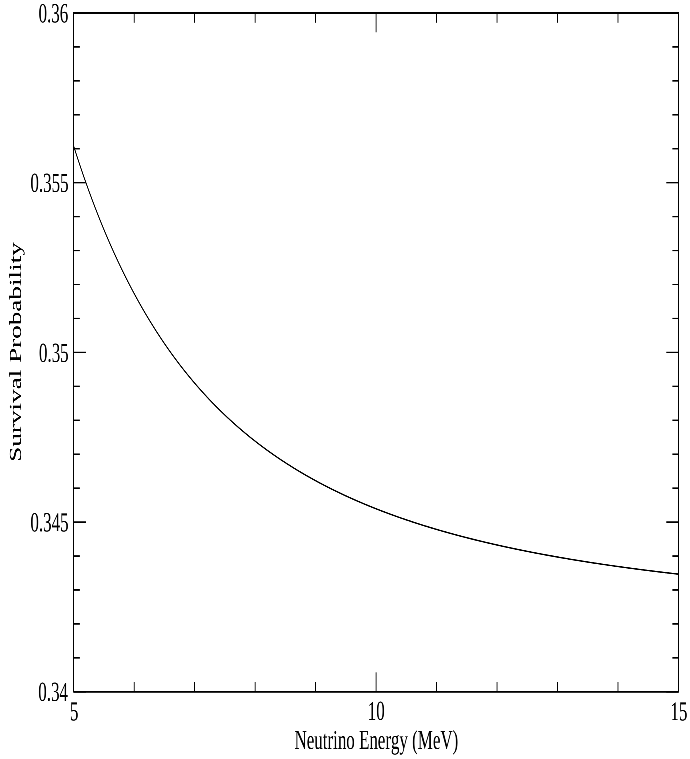

Figure 1: *LMA survival Probability for ^8B neutrinos as a function of energy for* $\sin^2\theta = 0.3418$.

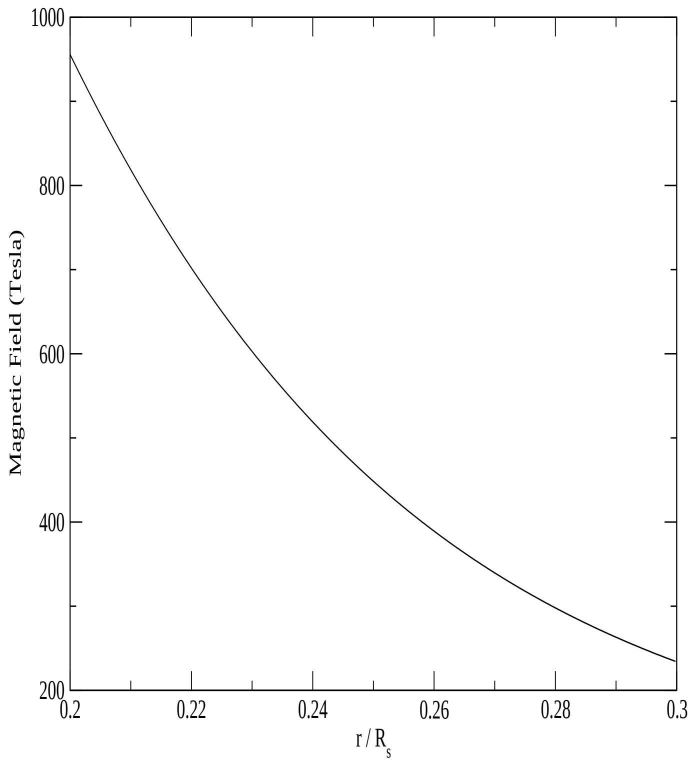

Figure 2: *The magnetic field profile in the resonance region of* ^8B *neutrinos.*